MELT LAYER MACROSCOPIC EROSION OF TUNGSTEN AND OTHER METALS UNDER PLASMA HEAT LOADS SIMULATING ITER OFF-NORMAL EVENTS

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This paper is focused on experimental analysis of melt layer erosion and droplet splashing of tungsten and other metals under heat loads typical for ITER FEAT off-normal events, such as disruptions and VDE's. Plasma pressure gradient action on melt layer results in erosion crater formation with mountains of displaced material at the crater edge. It is shown that macroscopic motion of melt layer and surface cracking are the main factors responsible for tungsten damage. Weight loss measurements of all exposed materials demonstrate inessential contribution of evaporation process to metals erosion.

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1. INTRODUCTION

Materials irradiation with plasma streams generated by powerful plasma accelerators [1,2], which can simulate at least in magnitude of heat load, the conditions expected for ITER off-normal events, is used at present for numerical models validation and for experimental simulation of metal targets erosion under high heat loads.

During such off-normal events as disruptions and vertical displacement events (VDEs) energy flux at the armour material reaches values sufficient for melting of metal surfaces. The melt layer is subjected to external forces such as surface tension, gradients of both plasma pressure and recoil pressure of evaporating material, Lorentz force and others. Melt motion driven by external forces may produce significant macroscopic erosion of materials [3,4]. It is expected that under the VDE rather large area of surface will be heated with a practically constant heat load. In contrast to VDE, during disruptions heating occurs with a characteristic heat load profile having the peak value at the separatrix strike point (SSP). As a consequence, the external pressure and surface tension depend on the position along the melt surface. Results of numerical simulations of disruption have shown that the pressure profiles of the plasma shield after 4 ms are between 4 and 7 bar and the pressure profiles have a half width of 4 cm only [5].

This paper presents the experimental analysis of contribution of different erosion mechanisms to the material damage under high heat loads simulating these features of VDE and disruption.

2. EXPERIMENTAL SETUP

Different metal targets were exposed to perpendicular and inclined plasma impact in QSPA Kh-50, which is described elsewhere [1]. The parameters of the free hydrogen plasma stream at the target position were as follows: average density of $4x10^{16}$ cm^{-3}, plasma stream energy density up to 25-30 MJ/m^2, ion energy below 0.6 keV, discharge duration t= 0.3 ms and power pulse duration (half height width) – 0.10-0.14 ms. Plasma stream maximal pressure in near the axis region achieved $(1.6\text{-}1.8)x10^6$ Pa. The diameter of the QSPA plasma stream was 10-12 cm. The total energy of the plasma stream exceeded 160 kJ. A guiding magnetic field of 0.54 T was applied in experiments (average $\beta \sim 0.3\text{-}0.4$).

A profilometer with an accuracy of 0.4 μm was used for analysis of the surface of the melt layer. As the sensitive element, a small ball was applied instead of a diamond pin for surface profile measurements to avoid surface roughness contribution to the profilograms. The unexposed part of the target was used as a reference for profilometry. Surface analysis was carried out with an optical microscope. X-ray diffraction analysis and weight loss measurements were performed also.

Radial distributions of plasma stream pressure measured by piezodetector at the target position are presented in Fig. 1 As follows from this figure, in spite of high values of pressure achieved in QSPA plasma stream, rather small pressure gradient is in the central part of the plasma stream corresponding to the targets position usually used.

That is why, for simulation of disruptions the targets were exposed through molybdenum diaphragms of different diameters to impose a pressure gradient along the target that mimics the pressure gradient found at the strikepoint locations in a tokamak disruption. Such experimental scheme is described in details in [6].

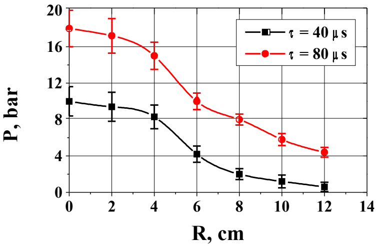

Fig.1. Radial distributions of plasma stream pressure at the target position

3. MELT MOTION

The profile of tungsten melt surface is presented in Fig. 2,a for perpendicular exposure with 20 pulses through the 2 cm hole. As it follows from profilometry, mountains of melt materials, indicating the melt motion, arise at the melt edge. The height of the mountains achieves 65 μm. The high value of the surface roughness $R_z \sim 30$ μm masks an erosion crater between the mountains and the ball sensor scans only the roughness peaks. Only tendency of crater formation is registered. It should be mentioned that even for a target thickness of 6 mm the influence of bending is seen on the profilograms. Sagging of the center of the target is about 10 μm, although initially it has a good flatness. Profile of melt spot of inclined tungsten target ($\alpha=20^0$) irradiated with 20 pulses through the 2 cm hole is presented in Fig. 2,b. The specific heat flux for exposure of an inclined target became essentially less (as compare with the perpendicular impact) due to the increase of the plane projection of the plasma stream to the target surface Formation of the mountain peak of 28 µm in height under the melt motion is observed at the downstream part of the melt spot only. Therefore the melt motion is dominated by plasma pressure. Contribution of surface tension gradient is insignificant and not seen against a background of triggered surface roughness.

Dynamics of the erosion crater and mountains formation in dependence on irradiation dose is shown in Fig.3 for irradiation of Ti sample through the 1 cm hole. The erosion crater with uniform depth is clearly registered even for exposure with one pulse because of the lower level of surface roughness and more pronounced melt motion for Ti.

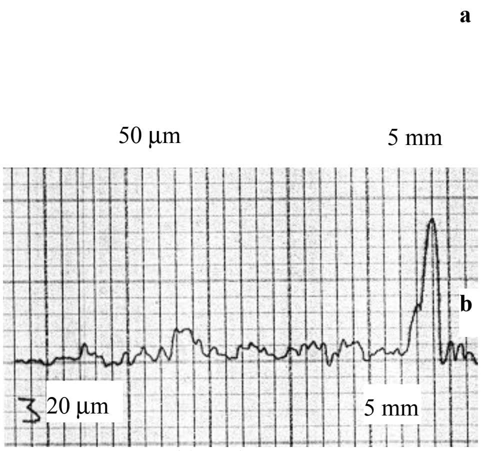

Fig.2. Erosion profiles of tungsten targets exposed with 20 pulses through the 2 cm hole; a- perpendicular impact, b- inclined plasma impact with $\alpha=20^0$

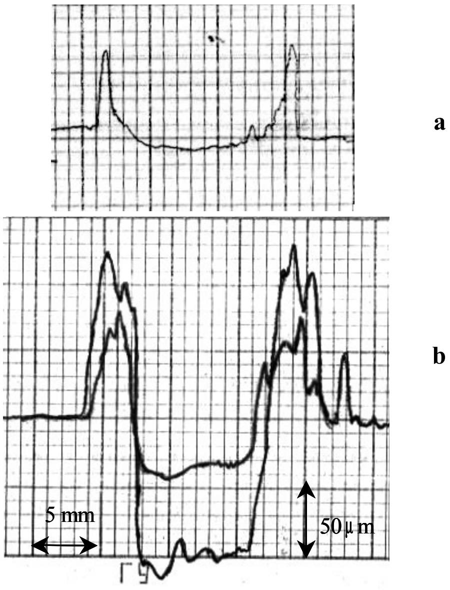

Fig. 3. Growth of erosion profile for Ti target under perpendicular plasma impact; a- 1 pulse, b- 5 and 20 pulses

Due to the thermo-mechanical properties of Ti (density, heat conductivity and melt temperature) higher melt velocities and melt layer depth are realized. Depth of erosion crater (i.e. erosion by melt motion) achieved 10-12 µm/pulse. The height of ridge arisen as result of first pulse action is up to 70 µm. There is an approximate balance between material loss in the crater area and mountain material. It was obtained that erosion crater depth and the distance between mountain peaks increased with the number of pulses and achieved 100 µm and 15 mm respectively after 15 pulses. The height of the mountains achieved 130 µm, their width was also increased up to 4-6 mm. With a further increase of the irradiation dose growth of the erosion crater and mountains became essentially slower, because of the resolidified mountain, restricts movement of the melt initiated by consequent pulses. Erosion evaluated from weight loss measurements for titanium targets is about 0.08 µm/pulse i.e. is negligible in comparison with erosion by melt movement

Increase of hole diameter leads to changes in pressure distribution along the target surface. Region with practically constant pressure appears in the central part (Fig.4). In this case registered erosion crater is nonuniform with a maximal depth at the periphery (region of maximal pressure gradient).

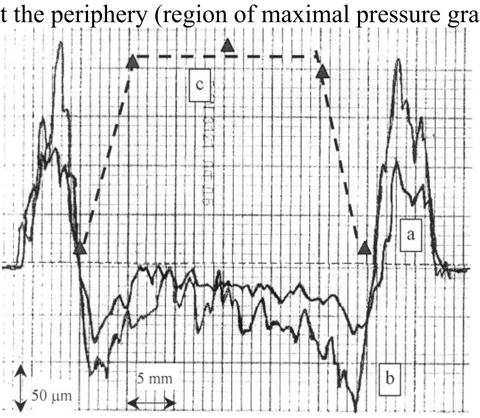

Fig.4. Melt layer profiles for titanium target irradiated with 10 pulses (a) and with 20 pulses (b), with overlay of plasma pressure profile (c). Vertical scale for pressure is 3.5 Bar/div. Hole diameter is 3 cm.

4. TUNGSTEN CRACKING

X-ray diffraction analysis of irradiated tungsten has shown a decrease of the tungsten crystal lattice period. It has appeared equal 3.1622 Å, while for initial nonirradiated surface the lattice spacing is 3.1653 Å. This is the result of compressive stresses, which arise in the resolidified layer and are accompanied by plastic deformation of material. Appearance of macrostresses leads to crack formation on the tungsten surface. Both fine intergranular and large size cracks are seen on target surfaces (Fig. 5). Thus alongside with melt motion, the surface cracking is very important process from the point of view tungsten damage. Nevertheless, measurements of weight loss shows negligible role of evaporation process in tungsten erosion. In terms of erosion crater weight losses are about 0.04 µm/pulse. To explain this result it should be noted that droplet splashing (including one caused by melt motion and surface cracking) is practically not contribute to weight loss because of overwhelming majority of ejected droplets remain on the sample surface. Lava flow observed at the edge of melt spot. Large cracks are not registered in this region. Droplets splashed to nonirradiated surface are observed also. Some tracks of droplets ejected from the melt are seen at the distance up to 1 cm from the melt spot. The size of droplets is varied in the range of 1µm-100µm. The quantity of droplets is in inverse proportion on their size. Analysis of droplets tracks have shown that droplets registered far from the melt edges were ejected with extremely high velocities (at least tens meters per second)

One of possible ways to improve the durability of tungsten against a cracking is use of tungsten coatings on

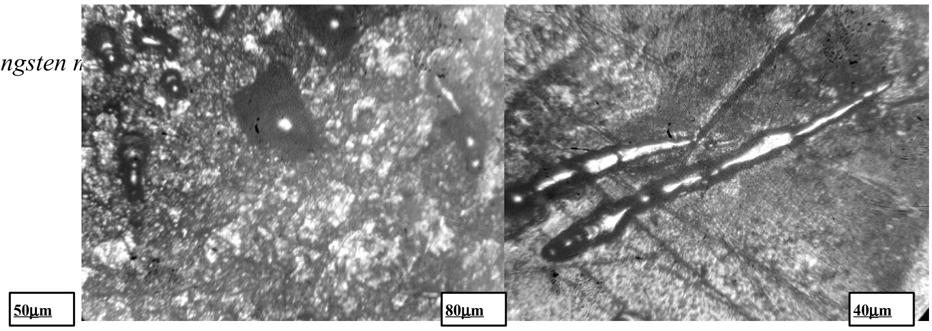

Fig.5. Images tungsten r

other materials instead of massive tungsten target. Such coatings are widely used in present-day tokamaks. As the first step in investigations of W-coatings erosion, the experiments on perpendicular and inclined irradiation of Cu targets with W-coatings have been started. Tungsten coatings were deposited with the planar ECR plasma source [7]. The thickness of W-coatings was 2 µm. The main results of coatings exposure can be summarized as follows:

Coating demonstrates rather high adhesion with substrate. High heat load do not lead to shelling and exfoliation of coating. In regimes of irradiation with energy loads below the coating melting point, excellent durability of the coating is observed. Even in conditions of melting under the high heat load no shelling and exfoliation were registered. As result of the surface melting under the plasma exposure some mixing of coating with material substrate is observed. Due to relatively small thickness of the coating molten copper appears on the surface at the places of grain boundaries. Erosion by melt motion for W-coated samples is similar to tungsten targets. However surface cracking is essentially less pronounced. Last result can be considered as important advantage of coatings in comparison with monolithic target.

5. SIMULATION OF VDE

Simulation of VDE is carried out with targets irradiation without diaphragms. In this case the heat load and plasma pressure are only slightly changed along the target surface and melt zone up to 8-10 cm in diameter can be achievable. Experiments have shown that the surfaces of the resolidified melt layers have a considerable roughness with microcraters and a ridge like relief on the surface. Melt layer erosion by melt motion was clearly identified only for exposure of composite targets [8]. Because of small value of pressure gradient in plasma shield the melt motion is masked by boiling, bubble expansion and bubble collapse and by formation of a Kelvin-Helmholtz instability. It is not clearly seen against a “background” of triggered high surface roughness, which became the main erosion factor.

6. CONCLUSIONS

The disruption simulation experiments have shown that metals erosion is dominated by melt motion. For perpendicular plasma impact the melt layer motion driven by plasma pressure gradient results in erosion crater formation with rather large mountains of the resolidified material at the crater edges. Analysis of plasma pressure distributions along the surface exposed through the diaphragms with different holes allows us to conclude that the most pronounced melt motion (and maximal erosion crater) is registered in the regions of the maximum gradient of plasma pressure.

Effect of deceleration for the erosion crater depth and mountain growth with increasing the number of exposures was observed. It is concluded that resolidified mountain, formed by previous pulses, restricts movement of the melt initiated by the consequent pulses.

Melt motion of metals is accompanied by droplet splashing. The droplets size is varied from 1 to 100 microns. The droplet velocity was evaluated on the basis of the droplet size, the distance of their displacement and the duration of the incident plasma stream exposure. The estimated velocity depends on their size and is typically more than 5.10^2 cm/s. Analysis of tungsten droplets tracks have shown that droplets registered far from the melt edges were ejected with extremely high velocities.

Exposure of inclined targets results in formation of mountain only at the downstream part of the target surface. This is a clear indication of plasma pressure influence. Under the conditions realized in the QSPA the surface tension gradient is not a determining factor for mountains formation and melt motion is dominated by plasma pressure.

Weight loss measurements of all exposed materials demonstrate inessential contribution of evaporation process to metals erosion.

Tungsten targets show highest erosion resistance in comparison with other metals. Nevertheless melt layer motion and surface cracking are the main factors responsible for tungsten damage. For ITER disruptions with much longer duration of plasma exposure, the melt motion can be very serious problem, especially in the case of additional action of Lorentz force due to the currents flowing in the melt

Erosion by melt motion for W-coated samples is similar to tungsten targets. However surface cracking is essentially less pronounced.

Triggered surface roughness became the dominating erosion factor only in the case of small values of driving forces for the melt motion initiation.

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Irradiation of composite copper SS- copper target was performed to make visible the material displacement by melt motion and to estimate the value of such displacement. Stainless steel rod of 5 mm in diameter was molded into the hole in copper target. Displacement of SS material due to the melt motion is 1.8-2 mm for perpendicular exposure with 20 pulses. Melt displacement in downstream direction for inclined with 30^0 target is about 1.5-1.8 mm after 40 pulses.